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Mao, C and Gao, Steven and Wang, Y and Sanz-Izquierdo, Benito and Wang, Z and Qin, F and Xin Chu, Q and Li, Jianzhou and Gao, W and Xu, J (2016) Dual-Band Patch Antenna with Filtering Performance and Harmonic Suppression. IEEE Transactions on Antennas and Propagation, 64 (9). pp. 4074-4077. ISSN 0018-926X.

DOI

http://doi.org/10.1109/TAP.2016.2574883

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Document Version

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Dual-Band Patch Filtering Antenna with Tunable bandwidth and Harmonic Suppression

Chun Xu Mao, Steven Gao, Yi Wang, Benito Sanz-Izquierdo, Zhengpeng Wang, Fan Qin, Qing Xin Chu, Jianzhou Li, Gao Wei, Jiadong Xu

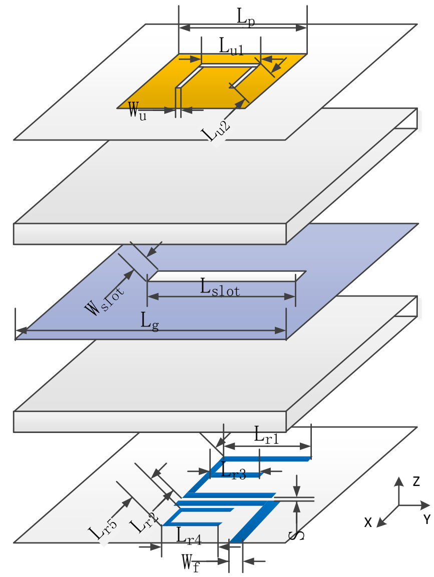
Abstract— A novel design of a dual-band antenna with integrated filtering performance is proposed. A low-profile aperture-coupled U-slot patch antenna is employed for dual-band operation with a consistent polarization. A dual-mode stub-loaded resonator (SLR) is used to feed the U-slot patch, which works as the last-order dual-mode resonator of the dual bandpass filter. The odd- and even modes of the SLR are coupled and tuned the two modes of the patch, resulting in two 2nd-order operation bands at 3.6/5.2 GHz. Compared with the traditional patch antenna, the proposed antenna exhibits an improved bandwidth and frequency selectivity. In addition, the bandwidths are tunable by adjusting the coupling strength between the SLR and the patch. Furthermore, the high-order harmonics over a broadband can be suppressed without increasing the footprint of the design. Measured and simulated results agree well with each other, showing an excellent performance in terms of impedance matching, bandwidths, 2nd-order filtering, out-of-band rejection, cross polarization discrimination (XPD) and gains at both bands.

Index Terms— Dual-band, bandwidth, 2nd-order, filtering, U-slot patch, harmonic suppression.

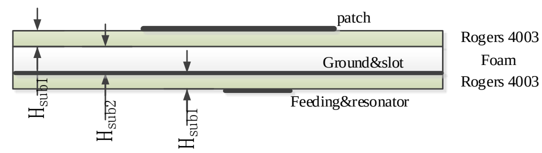
I. Introduction

THE modern wireless communication systems demand the RF front-end with the features of compact, highly integrated, multiband and multifunctional. Patch is one of the antennas widely used due to its advantages of low profile, low cost and compatibility with backend circuits. Significant effort has gone into designing dual-band or multi-band patch antennas [1]-[4]. Dual-band operation can also be obtained by manipulating the fundamental mode and higher order modes of the patch [5], [6].

To reduce the volume and complexity of the RF front-end and meet the demand for multifunctional operation, integrated designs of passive devices such as power dividers, filters and antennas have been considered as one promising solution. The integration has the added benefits of improving the frequency response and removing the 50 Ω interconnections and matching networks [8]. In [9], multiplexers were proposed based solely on resonators to eliminate traditional transmission-line based



(a)



(b)

Fig.1. Configuration of the proposed dual-band filtering antenna: (a) exploded perspective view, (b) the stacked structure.

distribution networks. The integration of filter and antenna has shown the advantages such as reduction of RF front-end [10], improved bandwidth and frequency selectivity [11] and harmonic suppression [12]. Nevertheless, many challenges are existing in the filtering antenna designs. One of them is that tunable bandwidth is usually required for an integrated design. Moreover, multiband filtering feature and higher order harmonic suppression are often demanded. To the authors' best knowledge, these problems haven't been fully considered and solved. In [13] and [14], two dual-band filtering patch antennas were proposed. However, the rectangular patch in [13] works in two orthogonal polarizations at the two bands and very complicated matching structures were adopted. Besides, the peak gains were only -1.8 dBi and 1.1 dBi at the two bands and lots of unwanted harmonics produced between the two bands. In [14], TM_{10} and TM_{30} modes of the patch were employed, but the gain is only -4 dBi and the feeding is complicated.

In this communication, a novel dual-band filtering antenna with broadband harmonic suppression performance is developed for 3.6/5.2 GHz WiMAX and WLAN applications. A dual-band U-slot patch antenna is integrated with a dual-mode stub loaded resonator (SLR) through electromagnetic

This manuscript is submitted on October 31, 2015. This work is supported by the project "DIFFERENT" funded by EC FP7 (grant no. 6069923). YW is supported by UK EPSRC under Contract EP/M013529/1.

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coupling, producing a 2nd-order dual-band filtering antenna. Compared with tradition patch, the bandwidth, filtering and harmonics suppression are significantly improved. In addition, the bandwidths of the antenna are tunable in the designing. Both the simulated and measured results exhibit improved bandwidth and radiation performances.

II. Antenna Design

A. Configuration

Fig. 1 shows the configuration of the proposed dual-band filtering antenna. The design has a stacked structure composed of two substrates and a thin foam (1 mm) between them. The square patch is printed on the upper layer of the top substrate. A U-shaped slot is etched in the patch to achieve dual-band operation [3]. The patch antenna is fed through a rectangular aperture in the ground plane. The feeding line and the resonator are printed on the bottom layer of the lower substrate. A dual-mode SLR is employed to couple and tune with the two bands of the U-slot patch. Fig.1 (b) illustrates the stacked structure of the proposed design. Rogers 4003 substrate with a dielectric constant of 3.55 and a loss tangent of 0.0027 is used. The thickness of the substrates is 0.813 mm. All simulations are performed using High Frequency Simulation Software (HFSS 15) and the optimized parameters are listed in Table I.

B. Stub-Loaded Resonator

To achieve the filtering performance based on a traditional U-slot patch antenna, a dual-mode resonator (SLR) is employed to couple and synthetically tune with the patch. Different from the traditional method that simply cascades a filter with an antenna [12], the filtering and radiating components are seamlessly integrated in this work. The U-slot patch is served as the last-order dual-mode resonator of the 1st-order dual-band passband filter (SLR) as well as the radiating element. This contributes to a higher order filtering performance (2nd-order) while the antenna maintains a compact footprint.

Due to a highly freedom in controlling the modes, an E-shaped SLR is widely used as a dual-mode resonator in filter design. The SLR can be analyzed using the odd- and even-mode method, which have been previously detailed in [15]-[17]. When the odd-mode is excited, the center part of the SLR is equivalent as shorted end and the resonant frequency can be approximately derived as,

$$f_{odd} = \frac{c}{2\sqrt{\varepsilon_r}\,(2L_{r1} + L_{r2})} \tag{1}$$

When the even-mode is excited, the symmetrical plane can be viewed as opened end and the resonant frequency can be expressed as,

$$f_{even} = \frac{c}{2\sqrt{\varepsilon_r}\,(L_{r1} + L_{r2}/2 + L_{r3})} \tag{2}$$

where the fodd and feven are the odd- and even-mode resonant frequencies of the SLR. c is the light velocity in free space and εr is the effective permittivity. Thus, the odd-mode and even-mode resonant frequencies can be tuned easily by adjusting the dimensions of the SLR.

TABLE I
PARAMETERS OF THE PROPOSED ANTENNA: (MM)

L_p	L_{u1}	L_{u2}	W_u	L_g	L_{slot}	W_{slot}	L_{r1}
27.2	7.5	8	0.45	60	9.4	0.7	8.2
L_{r2}	L_{r3}	L_{r4}	L_{r5}	S	W_f	H_{sub1}	H_{sub2}
8	6.15	4.2	2.8	0.3	1.8	0.813	1

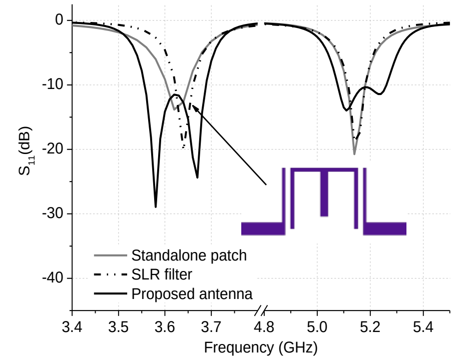
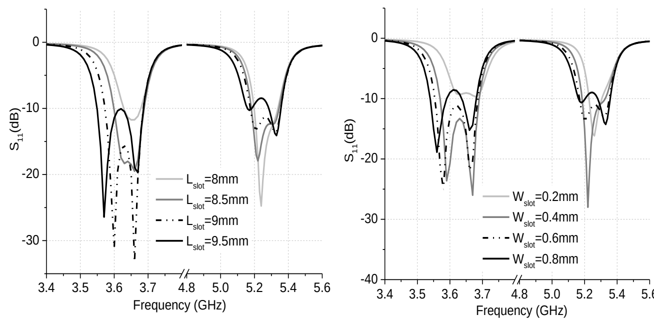


Fig. 2. The S_{11} comparison among standalone U-slot patch, SLR filter and proposed filtering antenna.



(a) (b)

Fig. 3. The variation of bandwidth with different: (a) Lslot, (b)

C. Improved Frequency Response

The bandwidth of the dual-band U-slot patch antenna is usually narrow, especially when the profile is low. Methods such as increasing the thickness of the substrate or adding air-gaps between the substrates are commonly used to increase the bandwidth at the expense of a higher profile [3]. In this design, a new method of enhancing the bandwidth is presented by integrating dual-mode resonator into the U-slot patch design to achieve a higher-order frequency response while maintain a low profile.

Fig. 2 compares the simulated S11 among the standalone U-slot patch, SLR filter and proposed filtering antenna. It is observed that the SLR-coupled U-slot patch antenna shows a 2nd-order frequency response with improved bandwidth of 4% at both bands and two reflection zeros identified in-band. In contrast, the traditional U-slot patch exhibits only one pole in each band and the bandwidths at both bands are only about 1.8%. Besides, the proposed antenna displays sharp roll-off at both bands, indicating an improved frequency selectivity.

D. Tunable Bandwidth

The bandwidth is one of the key issues to be concerned in filtering antenna design. In bandpass filter design, the bandwidth can be tuned by adjusting the coupling strength between the resonators [16]. In our previous work [17], the similar approach has been adopted to tune the bandwidth of the antenna.

Fig. 3(a)-(b) shows the variation of the bandwidths of the two bands with different lengths and widths of the aperture. It is observed that when the length of aperture Lslot is shorter than 8 mm, the two reflection zeros merge together, leading to a narrow bandwidth less than 50 MHz (FBW = 1.4%). As Lslot

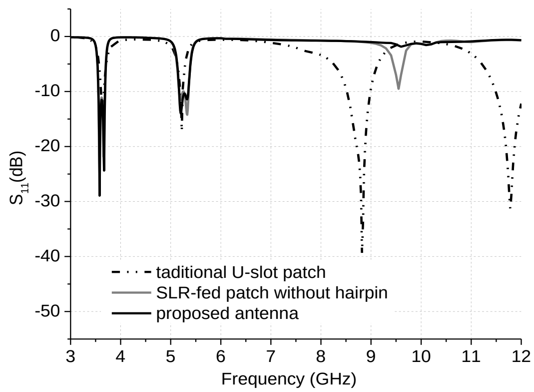


Fig. 4. The harmonic response of traditional U-slot patch, SLR-fed patch without hairpin and proposed filtering

increases, indicating the coupling strength between the SLR and the U-slot patch increases, the two reflection zeros are divided and a wider bandwidth of over 150 MHz (4.2%) is achieved for the low-band. The length of the aperture has a similar but less significant effect on the high-band operation. The effects of the width of the aperture on the bandwidth are depicted in Fig. 3(b). As can be seen that the width of the aperture decreases from 0.8 to 0.2 mm, the bandwidths of the low-band and high-band decrease from 4.2% to 1.9% and from 3.8% to 1.2%, respectively. Different from the traditional patch antenna, in which the bandwidth was usually tuned by adjusting the profile of the antenna, this work provides a new method to tune the bandwidth of the antenna while keep the profile of the antenna unchanged.

E. Harmonic Suppression

Harmonics is a serious problem to be concerned in wireless communication systems. Traditionally, the harmonics are often eliminated by cascading a filter at the backend [12]. However which will increase the complexity and the volume of the RF front-end. In this integrated filtering antenna design, harmonic suppression is taken into consideration. Fig. 4 shows the harmonic response of a traditional U-slot patch, a SLR-fed patch without hairpin and proposed filtering antenna. It is observed that the traditional patch antenna has two strong harmonics at 8.75 and 11.7 GHz. However when the U-slot patch is fed and coupled by a SLR, the two harmonics are eliminated. This is attributed to the fact that the dual-mode SLR and the dual-band U-slot patch have the same fundamental resonant frequencies but different higher order harmonics. As a result, these two components are detuned at the high band and the higher order harmonics can be suppressed.

It should also be noted that the SLR itself also introduces an unwanted harmonic at 9.5 GHz. To overcome this interference, a hairpin resonator with its fundamental resonant frequency at 9.5 GHz is shunted at the feed line, as presented in the proposed antenna. The hairpin resonator introduces a notch-band at 9.5 GHz, which is used to eliminate the interference at that band. As a result, this antenna can achieve an excellent out-of-band rejection up to 12 GHz. Compared with the traditional method in [12], the harmonics are suppressed without increasing the footprint of the antenna. In addition, the frequency response, including the bandwidth and the frequency selectivity, are significantly improved.

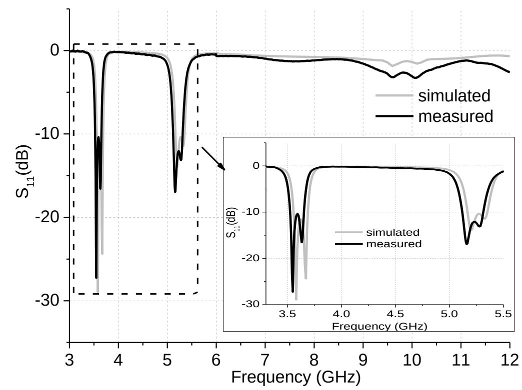
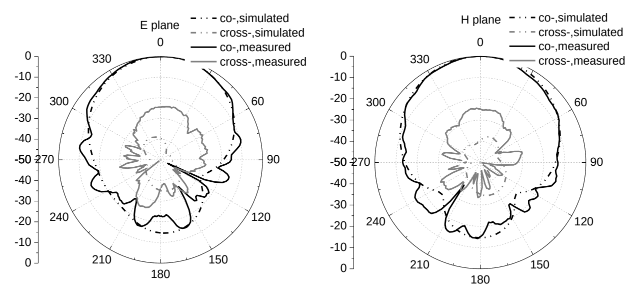
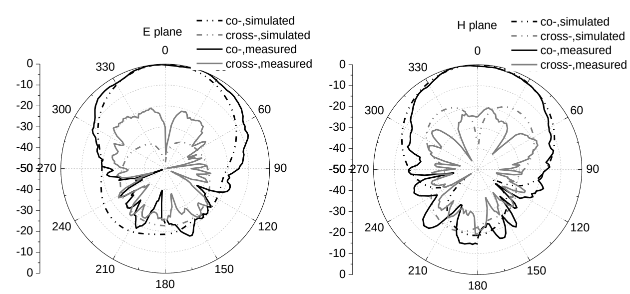


Fig. 5. Simulated and measured S_{11} of the proposed dualband filtering patch antenna.



(a) (b)

Fig. 6. The normalized simulated and measured radiation patterns at 3.6 GHz: (a) E plane, (b) H plane.



(a) (b)

Fig. 7. The normalized simulated and measured radiation patterns at 5.2 GHz: (a) E plane, (b) H plane.

III. Results and Discussion

The simulated and measured S11 of the proposed filtering antenna are presented in Fig. 5. A broad frequency range from 3 to 12 GHz is tested to show the harmonic suppression performance. The measured result agrees very well with the simulation with dual operation bands from 3.5 to 3.65 GHz and 5.1 to 5.3 GHz are achieved. The minor discrepancy between the simulation and the measurement is attributed to the fabrication errors. At the both bands, 2nd-order response with two reflection zeros are identifiable. This results in improved bandwidth and filtering performance. Out of the bands, the antenna exhibits wideband harmonic suppression up to 12 GHz.

Fig. 6(a)-(b) shows the normalized simulated and measured co- and cross-polarization radiation patterns at 3.6 GHz in the E (XOZ) and H plane (YOZ), respectively. The antenna exhibits a radiation in broadside direction with a cross polarization discrimination (XPD) of -25 dB in both planes. The E and H plane radiation patterns at 5.2 GHz are presented in Fig. 7. It is observed that the antenna has similar radiation patterns at the high band. Compared with the U-slot antenna in [3], the XPD of this antenna is significantly improved, especially in the directions offset the broadside. This is mainly attributed to the aperture-coupling is employed in the design. The discrepancy between the simulated and measured patterns, especially the backward radiation, is due to the influence of measurement devices and the cables behind the antenna.

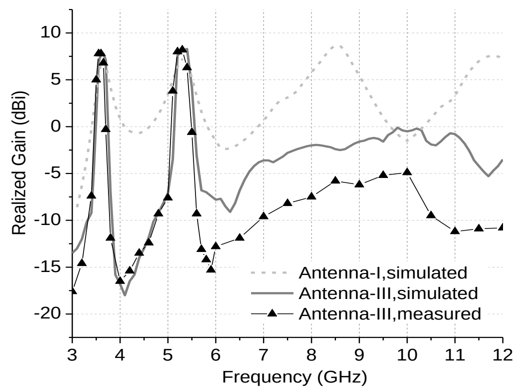


Fig. 8. The simulated and measured gain of the proposed dual-band filtering antenna.

TABLE II
COMPARISON WITH OTHER DUALBAND PATCH ANTENNAS

Types of antennas	Harmonics suppression	Polarization at two bands	Gain (dBi) (f_L/f_H)	XPD (dB) (f_L/f_H)
Ref. [13]	No	different	-1.8/1.1	-10/-22
Ref. [14]	No	consistent	-4.0/3.8	NA
This work	Yes	consistent	7.5/8.0	-40/-30

Fig. 8 shows the simulated and measured realized gains of the proposed dual-band filtering antenna from 3 to 12 GHz. For comparison, the simulated gain of a traditional U-slot patch antenna is also included. The proposed antenna achieve a gain of 6.5 and 7 dBi at low- and high-band, respectively. At the harmonics of 8.5 and 11.7 GHz, the traditional U-slot patch antenna has a gain of 7.5 dBi. However for the proposed filtering antenna, the gain drops sharply to below -7.5 dBi as the frequency offsets by 5.6% from the two central frequencies. At the two harmonic bands, the simulated and measured gains are significantly reduced to below -2 and -5 dBi, respectively. Thus, the proposed antenna demonstrates an excellent frequency selectivity and out-of-band suppression over a wideband due to the combined advantages of filter and antenna.

Table II compares the proposed dual-band filtering antenna in this communication with the other two reported dual-band filtering antennas in [13] and [14]. The comparison focuses on the harmonic suppression, polarization, gain and XPD at the two bands. This comparison shows that this work exhibits an improved gain and XPD at the two operation bands. The designs in [13] and [14] lack of the investigation of harmonic suppression and the gains are relatively lower than a traditional patch antenna. In addition, the work in [13] exhibits different polarizations at the two bands, and thus the technical contribution is insufficient.

IV. Conclusion

In this communication, a novel dual-band filtering antenna is proposed by integrating a dual-mode resonator in the U-slot patch antenna design. The U-slot antenna as well as the resonator are investigated. The proposed antenna exhibits an improved 2nd-order filtering response with two reflection zeros in both bands, which resulting in an enhanced bandwidth and frequency selectivity. The bandwidth can be tuned by adjusting the coupling strength between the SLR and the patch. In addition, the harmonic suppression over a broadband is investigated. Simulated and measured results agree well with each other, showing an excellent frequency response in terms of impedance matching, bandwidth, frequency selectivity, out-of-band rejection, radiation and gain.

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